RELATIONSHIP BETWEEN ROAD ROUGHNESS AND VEHICLE SPEED

Vladan Ilić[1]
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Summary: *In the past, numerous researchers and pavement proffesionals tried to find an analytical relationship between the road roughness and the vehicle speed which were measured on the same test sections. In HDM-4, special models were developed, in which maximum limiting speeds relative to road roughness condition were calculated. In this paper, a brief review of significant research conducted around the world that analyzed the influence of increasing road roughness, expressed through IRI, on the change of vehicle speed values, was given. The benefits and drawbacks of the results from previous studies were outlined, and the most important equations that define the relationship between the IRI and vehicle speed were presented. It has been found that the effect of pavement roughness on the vehicle speed is very small on the roads with IRI values less than 5m/km, such are usually the roads located in most developed countries.*

Keywords: *road roughness, pavement condition, vehicle speed, IRI, HDM, travel time.*

1. INTRODUCTION

International roughness index-IRI is a world-wide standard for measuring pavement roughness. The index measures pavement roughness in terms of the number of meters per kilometer that a laser, mounted in a specialized van, jumps as it is driven across the national road network. Therefore, IRI is one of the most relevant indicators of pavement condition with respect to road roughness. Since road deteriorate over time due to their exposure to the environment and to use, it is necessary to maintain them to ensure that they continue to provide an adequate level of service. Every defect of pavement surface, such as potholes and rutting, causes certain level of discomfort of travelling individual, both physical, e.g. bruises from an extremely bumpy ride, and psychological, e.g. anxiety due to a perceived increase in the probability of having an accident. Increased road roughness influences the costs of travelling in terms of lost time due to reduction of vehicle speeds. Some of the difficulties involved in determining relationship between pavement condition and the increase of travel time costs due to reduced vehicle speeds are:

- The relatively few tests that have isolated the road condition in the evaluation of its impact on vehicle speed;

[1]Research Assistant Vladan Ilić, MSc C.E. Faculty of Civil Engineering University of Belgrade, 73/I Bulevar Kralja Aleksandra, Belgrade, Serbia, tel: +381 11 3218 561, e – mail: vilic@grf.bg.ac.rs

- The continuous variation of speed along a road section, due to multiple factors, such as traffic behaviour, making it relatively difficult to obtain isolated information about speed and road condition at exactly the same location;
- The dependency of vehicle speed on road geometry, making comparisons between the studies published in literature virtually impossible.

2. PREVIOUS RESEARCH

One of the earliest studies into pavement roughness was by Karan, et al. [1]. Data were recorded on roughness, volume to capacity (v/c) ratios and spot speeds (using radar) at 72 locations. This paper is important in that it gives a good example of the problems associated with trying to quantify roughness effects through statistical modeling. Firstly, the authors had very small sample sizes: 32 % of the sites had less than 60 vehicles and 5 % less than 18 vehicles. These small sample sizes resulted in large standard errors. Unfortunately, the smallest samples corresponded to those pavements with the highest roughness thus limiting the accuracy of the resulting models. Secondly, and more importantly, no allowances were made for the effects of environment on speeds. Since speeds have naturally varied between locations, it was necessary to correct this in the modeling. Karan, *et al.* [1] found a significant effect of roughness on speeds and presented four models for predicting these effects. However, the coefficients in their models were inconsistent and raised doubts as to the accuracy of the approach. Du Plessis, *et al.* [2] investigated roughness effects on speed with the objective of calibrating the HDM-III speed prediction model. Data were collected on 22 straight, level sections on two-lane and dual carriageway roads. The sites were strongly biased towards smooth pavements, with 64 % having a roughness below 2,3 IRI. Only five pavements had roughness above 4,6 IRI, four of which were unsealed roads. A series of regression models were developed from the data. However, when the models were tested for autocorrelation, it was found that for all vehicles except heavy trucks, road type had a greater impact on speed than roughness. Thus, all the regression models were rejected as invalid. The India study [3] obtained roughness effects through a multivariate analysis where roughness was one term in the model. The Kenya study (Hide, *et al.* [4]) did not quantify a statistically significant roughness effect but Watanatada [5] extrapolated the Kenya unsealed road results to sealed roads. The measurements of response type roughness meters constitute the vertical displacement of the chassis relative to the axle over a section of road. This is termed the Average Rectified Slope (ARS) and is usually expressed in units of m/km or mm/m. Most studies directly related speed effects to the ARS. However, Paterson and Watanatada [6] found that the average rectified velocity was a better statistic to use since it "best represents the level of excitation in a moving vehicle". For the Brazil Study data, the ARS was expressed as 1,15 IRI (Watanatada, *et al.* [7]). By establishing the maximum acceptable level of excitation of a vehicle, the speed could be predicted as a function of this maximum level and the ARS. Watanatada, *et al.* [8] developed the following equation for predicting the average rectified velocity at any speed:

$$ARV(v) = a2\ IRI\ v \left[\frac{v}{22,2}\right]^{(a0 + a1 \ln (a2\ RI))} \qquad (1)$$

The values of various coefficients, as reported in [8], are given in ***Table 1***.

Table 1*: Regression Coefficients for Predicting ARV [8]*

Surface type	a0	a1	a2
Asphaltic concrete	0	0	1,15
Surface treated or gravel	1,31	-0,291	1,15
Earth or clay	2,27	-0,529	1,15

For the purposes predicting the speed, the maximum average rectified velocity (ARVMAX) had to be defined, since its value would give the maximum speed of a vehicle at a given roughness level. This resulted in the following equation:

$$v = \exp \frac{\ln \frac{ARVMAX}{a2\ IRI} + (a0 + a1 \ln (a2\ IRI)) \ln (22,2)}{1 + a0 + a1 \ln (a2\ IRI)} \qquad (2)$$

where ARVMAX was the maximum average rectified velocity in mm/s. For asphaltic concrete surfaces (where a0 and a1 = 0) equation (2) was simplified to:

$$v = \frac{ARVMAX}{a2\ IRI} \qquad (3)$$

3. HDM-III SPEED PREDICTION MODEL

In HDM-III equation (3) was used for all surface types. Using data from the Brazil study, Watanatada, *et al.*, [7] calculated the values for ARVMAX given in ***Table 2*** for the HDM-III model. The values decreased as one moved from the softer suspensions of passenger cars to the firm suspensions of heavy commercial vehicles. This indicates that lighter vehicles will have higher speeds on rough roads than heavy vehicles.

Table 2*: Maximum Average Rectified Velocity by Vehicle Class [7,9]*

Vehicle Class	Maximum Average Rectified Velocity (mm/s)	
	Brazil	Australia
Passenger Cars	259,7	203
Light Commercial Vehicles	239,7	200
Heavy Buses	212,8	-
Medium Commercial Vehicles	194,0	200
Heavy Commercial Vehicles	177,7	180
Articulated Trucks	130,9	160

In Australia, McLean [9] derived roughness effects values for equation (3) indirectly from a user survey. On rougher pavement sections, users were asked to state the additional distance they would be prepared to travel to make the journey on a smooth road section. For the roughest section in the survey (IRI = 6,7), the difference in journey distances were converted into different travel speeds for the same journey time. The parameter ARVMAX was adjusted to match the predicted steady state speed with the travel speed calculated for IRI = 6,7. The resulting value for ARVMAX was very close to that in HDM-III. ***Table 2*** lists the Australian values for ARVMAX [9].
Elkins and Semrau [10] presented equivalent models to equation (3) for cars and trucks in the U.S.A. based on data from Brazil and the U.S.A. analytical process and data surveys. Cox [11] suggested that roughness did not impact on speeds for smooth roads, citing an Australian study which found that it was only above 5 IRI m/km that speeds were affected by roughness.

4. ROAD ROUGHNESS AND VEHICLE SPEED ON SWISS ROADS

In a very comprehensive study, the methodology and base cost models to determine the total benefits of preservation interventions on road sections in Switzerland, were developed by Adey, Herrmann et al. [12]. The road condition in Switzerland is approximated based on pavement condition, which is measured using six indices as presented in VSS 2003b [13]):

- I0 is used to measure surface damage without taking ruts into consideration;
- I1 is used to measure surface damage taking ruts into consideration;
- I2 is used to measure longitudinal unevenness (roughness);
- I3 is used to measure transversal unevenness;
- I4 is used to measure surface friction;
- I5 is used to measure the load carrying capacity of the road section.

Thus, the road roughness in Switzerland isn't represented by IRI index, although the index I2, by its definition, most closely matches the physical meaning of the IRI.
Previous study [12] is very important because it defines the relationship between travel time costs and pavement condition. These costs vary indirectly as a function of pavement condition, i.e. pavement condition affects the speed of driving, and therefore, the amount of time required to complete a specific trip, once certain road condition thresholds (road roughness values) have been reached. Usually, these thresholds are defined per road category. In this study, the relationship between speed and pavement condition was determined based on the research of Bennett and Greenwood [14]. The index I2 was considered to be an adequate representation of pavement condition for the estimation of travel time costs. The travel time costs C_{TT} are then calculated as:

$$C_{TT} = UC_{TT} \cdot t \cdot ADTV \tag{4}$$

where UC_{TT} is the unit cost of travel time per vehicle and $ADTV$ is average daily traffic volume. Travel time per vehicle t is calculated as [12]:

$$t=\frac{s}{v_{tech}}\left(1+\alpha\left(\frac{u}{cap}\right)^{\beta}\right) \quad (5)$$

where:

s = road section length upon which each vehicle travels;
α = the parameter dependent on road characteristics;
β = the parameter dependent on road characteristics;
cap = the road capacity, expressed as number of vehicles per unit time;
u = the traffic flow during analyzed interval;
v_{tech} = the free flow speed.

In this study, it is assumed that the relationship between I2 and IRI can be linearly approximated from the difference in the I2 values that correspond to the IRI values between 5m/km and 6 m/km, and IRI values less than 5 m/km have no effect on speeds.

5. CONCLUSION

While the multivariate analyses generally found statistically significant roughness effects, and the HDM-III model developed a limiting roughness-speed model, there are always problems ensuring that the effects are being correctly predicted. The approach used in developing all previous models relied on statistical estimation to differentiate between the factors simultaneously influencing speeds. Given the multiplicity of factors influencing speeds it is not always certain that the roughness effects have been accurately isolated. Previous studies have shown that there are major problems with attempting to investigate roughness effects by pooling data from different sites, especially from the road sections with different geometric alignment. The roughness effects can be expected to be small, particularly on roads with low levels of roughness (IRI < 5,0) such are usually found in developed countries, e.g. Switzerland. When the other factors influencing speeds, particularly road environment, are taken into account, these effects are often lost.

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VEZA IZMEĐU RAVNOSTI PUTA I BRZINE VOZILA

Rezime: *U prošlosti brojni istraživači i profesionalci iz oblasti kolovoznih konstrukcijia nastojali su da pronađu analitičku vezu između ravnosti kolovoza i brzine vozila merenih na istim testnim deonicama. U HDM-4 razvijeni su posebni modeli u kojima se proračunavaju maksimalne ograničavajuće brzina vozila u odnosu na stanje ravnosti kolovoza. U ovom radu dat je sažet prikaz značajnih istraživanja sprovedenih širom sveta u kojima je analiziran uticaj povećanja neravnosti puta, izražen preko IRI-a, na promenu vrednosti brzina vozila. Ukazano je na prednosti i mane dobijenih rezultata iz dosadašnjih istraživanja i prikazane su najvažnije relacije koje definišu zavisnost između IRI-a i brzine vozila. Ustanovljeno je da je efekat ravnosti kolovoza na brzinu vozila veoma mali na putevima sa vrednošću IRI-a manjom od 5 m/km, kakvi su obično putevi u većini razvijenih zemalja.*

Ključne reči: *ravnost puta, stanje kolovoza, brzina vozila, IRI, HDM, vreme putovanja.*